A new method for the experimental study of topological effects in the quark-gluon plasma

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A new method is presented for the quantitative measurement of charge separation about the reaction plane. A correlation function is obtained whose shape is concave when there is a net separation of positive and negative charges. Correlations not specifically associated with charge, from flow, jets and momentum conservation, do not influence the shape or magnitude of the correlation function. Detailed simulations are used to demonstrate the effectiveness of the method for the quantitative measurement of charge separation. Such measurements are a pre-requisite to the investigation of topological charge effects in the QGP as derived from the "strong $\mathcal{CP}$ problem".

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INTRODUCTION

Topological charge fluctuations play an important role in the structure of the QCD vacuum [1]. It manifests in the breaking of chiral symmetry, as well as in the mass spectrum and other properties of hadrons. These fluctuations can also lead to the formation of metastable vacuum domains, especially in the vicinity of the de-confinement phase transition, in which fundamental symmetries ($\mathcal{P}$ and/or $\mathcal{CP}$) are spontaneously broken [2] *i.e.* the so-called "strong $\mathcal{CP}$ problem". Experimental evidence for such topological fluctuations have been largely indirect.

Recently, it has been suggested that direct experimental signatures of topological fluctuations could result from quark gluon plasma (QGP) [quarks liberated from hadronic confinement] subjected to an intense (hadron-scale) external magnetic field, via the so called chiral magnetic effect (CME) [3, 4]. In brief, topological charge fluctuations in the QGP leads to an axial anomaly or local imbalance between left-handed and right-handed light quarks. In an intense magnetic field, these quarks move along the field to create a net electric current which results in a separation of positive and negative electric charges in the field direction. Evidence for the chiral magnetic effect has been found in recent numerical lattice QCD calculations [5]. An axial anomaly can also result from an anomalous global symmetry current in the hydrodynamic description of the QGP [6]. This results in a modification of the hydrodynamic current by a term proportional to the vorticity of the fluid, and manifests also as a separation of positive and negative electric charges perpendicular to the reaction plane. Hereafter, we term this as the chiral rotation effect (CRE).

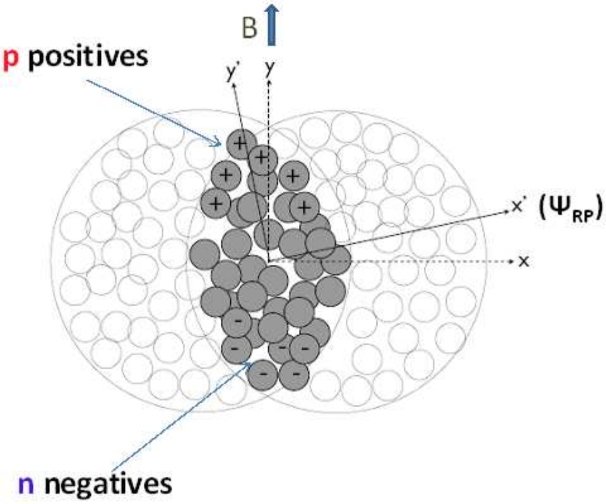

FIG. 1. Schematic illustration of the chiral magnetic effect. Colliding nuclei (depicted as circles) are moving in and out of the page respectively. The Magnetic field (B) and system orbital angular momentum (L) are perpendicular to the reaction plane (plane spanned by the impact parameter, b, and colliding nuclei direction). Note that the overlap zone is not necessarily aligned with B or L.

MEASURING TOPOLOGICAL EFFECTS

Collisions between heavy nuclei at the Relativistic Heavy Ion Collider (RHIC), not only create a strongly coupled low viscosity QGP [7–14] but also the strongest magnetic fields [orthogonal to the reaction plane] attainable in the laboratory [15]. Consequently, the chiral magnetic effect or the chiral rotation effect is expected to lead to a charge asymmetry in the distribution of particles emitted about the reaction plane (see Fig. 1). Experimental studies of such an asymmetry could provide an important avenue for investigating one of the most important problems of strong interaction theory.

The STAR collaboration has analyzed data from recent measurements of Au+Au and Cu+Cu collisions (at

$\sqrt{s_{NN}} = 200$ GeV) in search of this charge asymmetry with respect to the reaction plane. To do this they constructed a correlator which used the emission angles of like-sign ($++$ or $--$) and opposite-sign ($+-$) hadron pairs. The correlator is defined by the event average

$$C^{(\pm,\pm)} = \left\langle \cos\left(\phi_\alpha^{(\pm)} + \phi_\beta^{(\pm)} - 2\Psi_2\right) \right\rangle, \qquad (1)$$

where ϕ_α, ϕ_β denote the azimuthal emission angles of any pair of hadrons, and Ψ_2 denotes the azimuthal orientation of the estimated second order event plane. The difference

$$\Delta Q \sim C^{(++)} + C^{(--)} - 2C^{(+-)} \qquad (2)$$

was used to test for a charge separation [about the reaction plane] of the kind suggested by the CME and the CRE, after an appropriate correction for dispersion of the reaction plane.

A charge separation has been reported by the STAR collaboration [16, 17]. However, its mechanistic origin is still under intense debate [18–22]. One reason for this has been the observation that the correlator used in the STAR analysis may be sensitive to several well known "background" correlations such as elliptic flow, jets and momentum conservation [19, 21, 22]. Therefore, it is important to develop and investigate new correlators which can overcome many, if not all, of these deficiencies.

A full study of topological effects in the QGP and its implications for the "strong $\mathcal{CP}$ problem", will undoubtedly require further detailed measurements focused on accurate experimental quantification of the dependence of charge asymmetry on particle species, particle p_T, collision-system deformation, event centrality and beam collision energy. Here, we present a new experimental correlator specifically designed to aid such investigations.

Our technique involves a multi-particle charge-sensitive in-event correlator $C_c(\Delta S)$,which is expressed as a ratio of two distributions;

$$C_c(\Delta S) = \frac{N(\Delta S_{csep})}{N(\Delta S_{cmix})}. \qquad (3)$$

The numerator is a distribution over events of the event averaged quantity ΔS_{csep} defined as

$$\Delta S_{csep} = \left\langle S_p^{h+} \right\rangle - \left\langle S_n^{h-} \right\rangle \qquad (4)$$

where

$$\left\langle S_p^{h+} \right\rangle = \frac{\sum_1^p \sin(\Delta\varphi_+)}{p}, \;\; \left\langle S_n^{h-} \right\rangle = \frac{\sum_1^n \sin(\Delta\varphi_-)}{n}, \qquad (5)$$

n and p are the numbers of negative and positive hadrons [respectively] emitted about the observed event plane Ψ_{EP} ($m = n + p$ is the charge hadron multiplicity for an event) and $\Delta\varphi = \phi - \Psi_{EP}$ where ϕ is the azimuthal emission angle of the charged hadron.

The distribution ΔS_{cmix} in the denominator in Eq. 3, is obtained by making event averages in a slightly different way; That is, Eq. 5 is used to evaluate the averages $\left\langle S_p^h \right\rangle$ and $\left\langle S_n^h \right\rangle$ for p and n randomly chosen hadrons (irrespective of charge) i.e.

$$\Delta S_{cmix} = \left\langle S_p^h \right\rangle - \left\langle S_n^h \right\rangle. \qquad (6)$$

There are several important features of the new correlator $C_c(\Delta S)$. First, it is constructed entirely from a real event; hence, it is pure in event class (centrality, vertex, etc). Second, it is rather insensitive to the background correlations which influence reliable extraction of the magnitude of the charge-separation correlation (see discussion below). In what follows, we use detailed simulations to demonstrate the expected trends, as well as the efficacy of $C_c(\Delta S)$.

SIMULATION METHODOLOGY

The response of $C_c(\Delta S)$ to a charge-separation signal was tested via a detailed set of simulations tuned to reproduce observed experimental features. The simulations included the following major steps for each event.

- The event plane was chosen at random from 2π. Charged particles were then emitted with an azimuthal distribution with respect to this reaction plane as:

$$N(\Delta\varphi) \propto (1 + 2v_2\cos\Delta\varphi) + 2v_4\cos(4\Delta\varphi) + 2a_1\sin(\Delta\varphi), \qquad (7)$$

  where the Fourier coefficients v_2 and v_4 are the observed magnitudes of elliptic and hexadecapole flow, and a_1 is the charge-separation signal of interest. The number and p_T distribution of particles were tuned to match the experimentally observed distributions. The reaction plane was then dispersed according to the experimentally observed dispersion for the centrality selection under study.

- Neutral decay particles (e.g. Λ and K_0) were emitted with respect to the reaction plane according to their observed flow patterns. The decay kinematics of these resonances were followed so as to obtain the daughter particle directions and momenta. The relative abundance of the decay particles were constrained by the requirement that the simulated and observed positive-negative charge pair correlations (obtained by the standard event mixing method) were in agreement.

- Jet particles were emitted with respect to the jet axes in a manner which was consistent with the observed two-particle jet correlations.

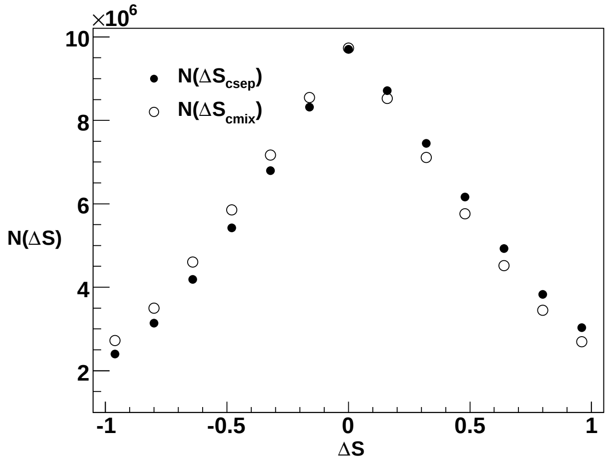

FIG. 2. $N(\Delta S)_{csep}$ and $N(\Delta S)_{cmix}$ distributions for simulations performed with $a1 > 0$ for all events.

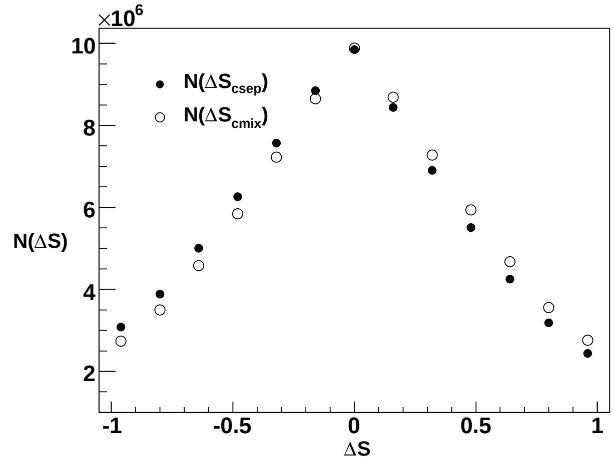

FIG. 3. $N(\Delta S)_{csep}$ and $N(\Delta S)_{mix}$ distributions for simulations performed with $a1 < 0$ for all events.

- All emitted particles were passed through an acceptance filter specifically designed to take account of the detector acceptance and consequently, reproduce the measured inclusive distributions for positive and negative hadrons respectively as a function of p_T.

- The simulated events were analyzed as if they were actual experimental events. The correlation $C_c(\Delta S)$ was evaluated for the selected range of p_T using the detected particles and the dispersed reaction planes using Eqs. 3 - 6.

RESULTS FROM SIMULATIONS

Simulations were performed for a broad spectrum of scenarios. Here, we show a representative set of results which lends insight into the detailed nature of $C_c(\Delta S)$, as well as its sensitivity to different sources of background correlations.

The distributions for $N(\Delta S)_{csep}$ (solid circles) and $N(\Delta S)_{mix}$ (open circles) are compared in Figs. 2 and 3 for $a_1 > 0$ and $a_1 < 0$ (respectively) for all events. Fig. 2 shows that for $a_1 > 0$ the distribution for $N(\Delta S)_{csep}$ is shifted to the right when compared to that for $N(\Delta S)_{mix}$. Similarly Fig. 3 shows that for $a_1 < 0$, the distribution for $N(\Delta S)_{csep}$ is shifted to the left when compared to that for $N(\Delta S)_{mix}$. Figs. 4 and 5 show the respective $C_c(\Delta S)$ distributions which result from the ratio of the distributions shown in Figs. 2 and 3. They indicate sizable deviations from a flat distribution with positive and negative slopes respectively. Note that a flat distribution would be indicative of no charge-separation. $C_c(\Delta S)$ distributions are shown in Figs. 6 and 7 for simulated events in which (i) 51% of the events were generated with $a_1 > 0$ and the other 49 % with $a_1 < 0$, and (ii) 49% of the events with $a_1 > 0$ and 51% of the events with $a_1 < 0$. In both cases, an asymmetric concave distribution is obtained but with opposite asymmetry.

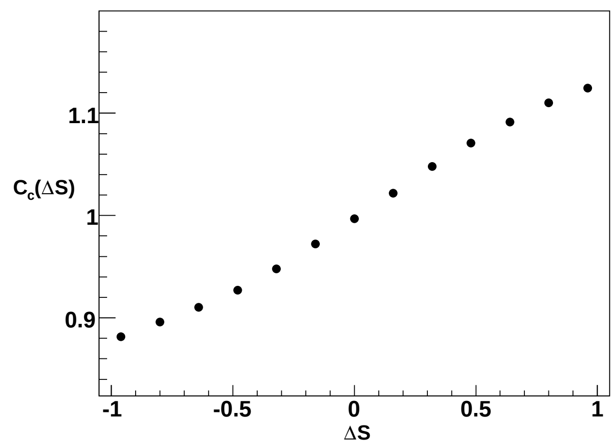

FIG. 4. Distribution for $C_c(\Delta S)$ obtained from the ratio of the distributions shown in Fig. 2.

The distributions for $N(\Delta S)_{csep}$ and $N(\Delta S)_{mix}$ obtained for a simulation in which 50% of the events were generated with $a_1 > 0$ and the other 50% with $a_1 < 0$ are shown in Fig. 8. This choice was made to mimic the effects of local parity violation implied by current models of topological charge generation in the QGP. For this scenario, Fig. 8 indicates that although the two distributions are strikingly similar, $N(\Delta S)_{csep}$ is slightly broader than $N(\Delta S)_{mix}$. This is made more transparent in Fig.9 by the symmetric concave shape obtained for $C_c(\Delta S)$ from the ratio of these distributions.

To investigate the influence of "background" correlations from flow, jets and resonance decays, several simulations were performed with these correlations turned

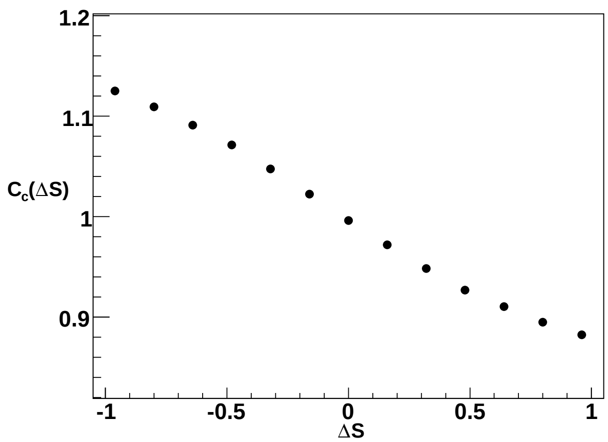

FIG. 5. $C_c(\Delta S)$ correlation function obtained from the ratio of the distributions shown in Fig. 3.

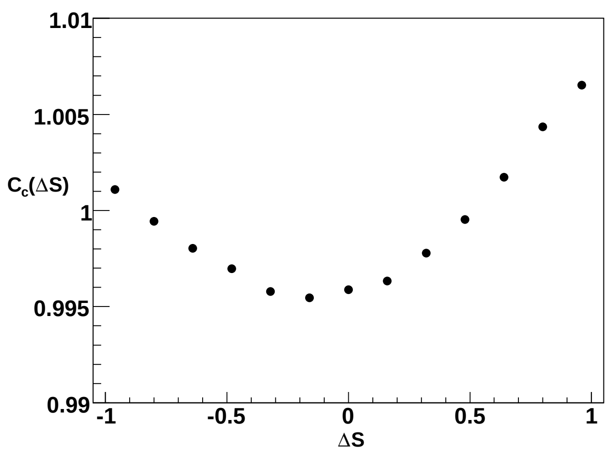

FIG. 6. $C_c(\Delta S)$ correlation function obtained with $a1 > 0$ in 51% of events and $a1 < 0$ in 49% of events.

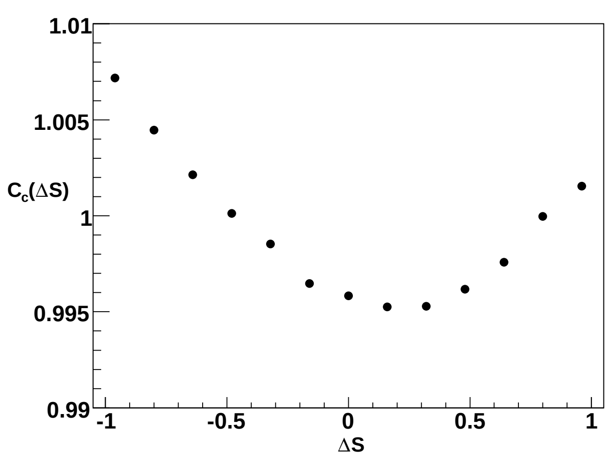

FIG. 7. $C_c(\Delta S)$ correlation function obtained with $a1 > 0$ in 49% of events and $a1 < 0$ in 51% of events.

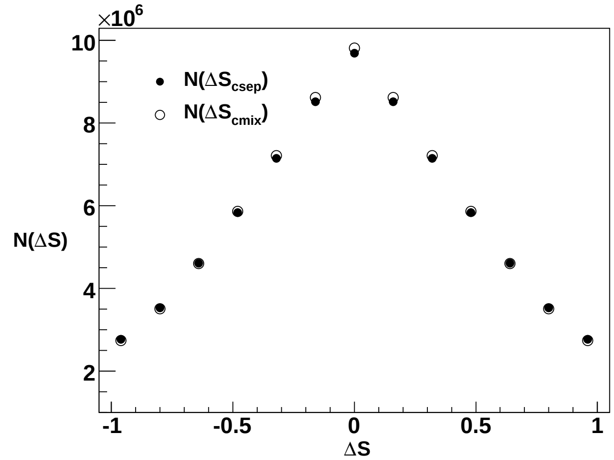

FIG. 8. Comparison of $N(\Delta S)_{csep}$ and $N(\Delta S)_{mix}$ distributions for simulations performed with $a1 < 0$ in 50% of the events and $a1 > 0$ in the other 50%.

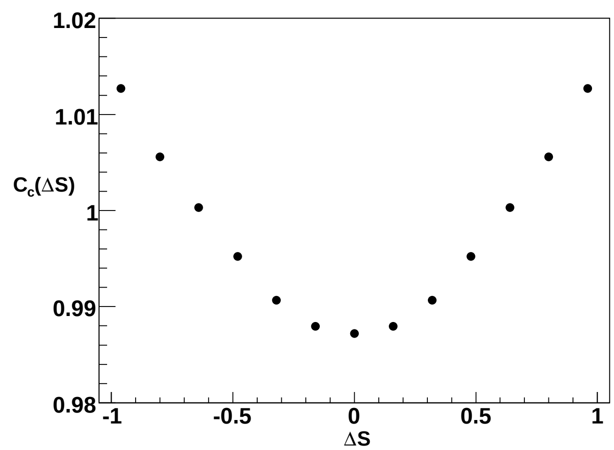

FIG. 9. $C_c(\Delta S)$ correlation function obtained from the ratio of the distributions shown in Fig. 8.

on or off. Fig. 10 shows the correlation function for a simulation in which only flow correlations are turned on for all events, i.e. $v_{2,4} \neq 0$, $a_1 = 0$ and resonance decays are turned off. The flat distribution indicated by Fig. 10 shows that $C_c(\Delta S)$ is insensitive to flow. In contrast to Fig. 10, Fig. 11 shows a convex shape for $C_c(\Delta S)$ which results from the charge correlations associated with resonance decays which tends to bring opposite charges closer together in azimuth than on average. For this correlation function, the simulation was performed with flow on, $a_1 = 0$ and resonance decays on, for all events. Since these correlations have an opposite influence on the shape of $C_c(\Delta S)$ [compared to that for the charge separation signal], it is important to have the relative abundances of decay particles properly incorporated into the simulations. This is ensured by requiring the

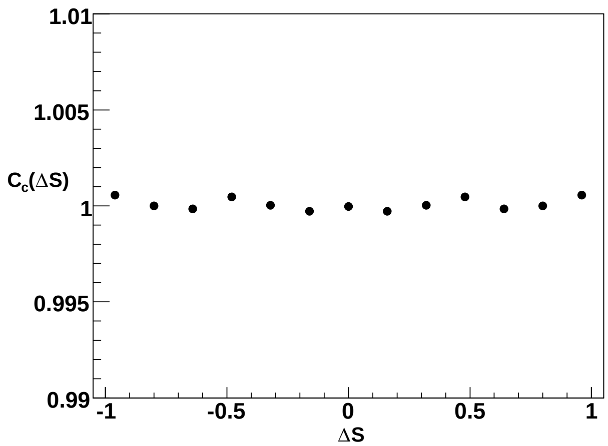

FIG. 10. $C_c(\Delta S)$ correlation function obtained for simulated events with only flow correlations.

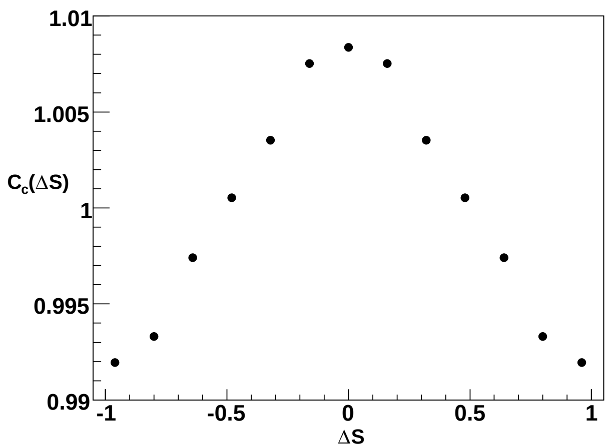

FIG. 11. $C_c(\Delta S)$ correlation function obtained for simulated events with flow on, resonance decay on and $a_1 = 0$.

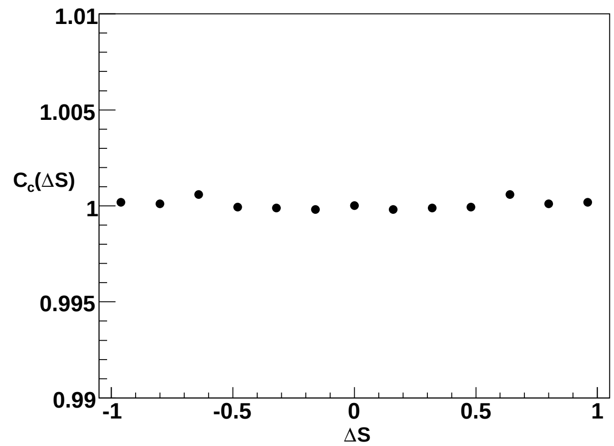

FIG. 12. $C_c(\Delta S)$ correlation function obtained for simulated events with jets on, flow on, no resonance decay and a_1=0.

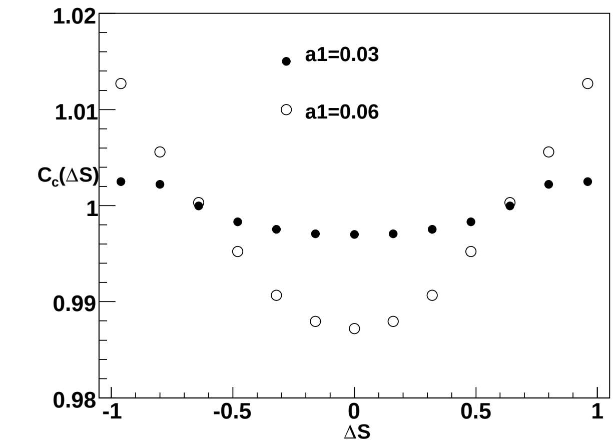

FIG. 13. $C_c(\Delta S)$ correlation functions obtained for simulated events with a_1=0.03 and a_1=0.06.

standard two particle opposite charge correlations from the simulations to match those for experimental data.

The correlation function shown in Fig. 12 was obtained for simulated events in which flow is on, $a_1 = 0$, resonance decays are off, but jets are turned on for all events. It is very similar to the flat distribution seen in Fig. 10 and confirms the absence of any significant background correlations to $C_c(\Delta S)$ from jets. Because the same event is used to construct both $N(\Delta S)_{csep}$ and $N(\Delta S)_{mix}$ momentum correlation effects are also not expected to play any significant role.

For an actual experimental correlation signal, the value of a_1 would be obtained by matching simulation to the observed correlation. The sensitivity of $C_c(\Delta S)$ to the the parameter used to specify the magnitude of the charge separation a_1 is demonstrated in Fig. 13. It shows that $C_c(\Delta S)$ is responsive even to a relatively small charge asymmetry.

It is important to stress that the method presented here is very general. For this study it has been applied to the correlations between charges in an event. However, our methodology can be applied to the investigation of correlations within any observed particle property.

SUMMARY

In summary, we have presented a new method which allows for good quantitative measurement of charge separation about the reaction plane. Our method involves the formulation of a novel correlation function $C_c(\Delta S)$ whose shape is concave only when there is a non-zero charge separation signal. The strength of $C_c(\Delta S)$ is related to the parameter a_1 which can be linked to a parity

violating signal. It is noteworthy that experimentally a reaction plane obtained from second order flow (v_2) has a $\pm\pi$ ambiguity. Introduction of such an ambiguity in the simulations makes all correlations symmetric i.e. the sensitivity to global parity violation would be lost since the sign of a_1 cannot be determined. However the sensitivity of the correlation function to the magnitude of a_1 remains. Correlations due to flow, jets and momentum conservation, do not influence the shape nor the magnitude of $C_c(\Delta S)$. Therefore, $C_c(\Delta S)$ measurements could provide an important framework for investigating one of the most important problems of strong interaction theory – the "strong $\mathcal{CP}$ problem".

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